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NEW PROBLEMS OF BALL LIGHTNINGS

M. T. Dmitriyev

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NEW PROBLEMS OF BALL LIGHTNINGS

M. T. Dmitriyev

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Mikhail Timofeyevich Dmitriyev heads the laboratory for physico-chemical and radiological research in the Institute of General and Communal Hygiene of AMN SSSR. His principal scientific interests are conntected with physics of the atmosphere, radiation chemistry of the air, and environmental protection. In addition, M. T. Dmitriyev carefully collects and interprets observations on ball lightnings.

Physico-chemical analysis of the traces of lightning

The problem of the nature of ball lightning is of general physical importance, particularly for the theory of electricity. At the same time, ball lightning is investigated by such specialized disciplines as meterology and physics of the atmosphere and the clouds. In the view of many investigators, a solution of the problems of ball lightning will stimulate the development not only of the physics of the atmosphere, but also of other sciences, and may lead to the discovery of new physical phenomena and relations.(1)

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* Numbers in the margin indicate pagination of original foreign text.

(1) See I. M. Imyanitov, Ye. V. Chubarina, Ya. M. Shvarts. Elektrichestvo oblakov (Electricity of Clouds), Leningrad, Gidrometeoizdat, 1971, p. 5.

Discussion of the nature of ball lightning, which was opened in this journal several years ago,[2] continues to evoke responses from the readers. In addition, the editorial office receives systematically new observational material on ball lightnings which has not been published anywhere. We shall attempt to analyze and generalize this new material.

Since ball lightning cannot be reproduced and studied in detail in scientific laboratories, the major role in solving the problem will be played as before by observations carried out under actual conditions. As a rule, descriptions of eyewitnesses indicate there is considerable energy in ball lightning. As an illustration, we shall describe here an interesting study of ball lightning observed on August 13, 1969 in the village, Yamskie Lesa, near the town of Noginsk in the Moscow area. The study was carried out by A. S. Bystrikov.

The news about this lightning was published on August 19, 1969 in the town newspaper "Znamya kommunizma" (Communism Banner) in an article by L. V. Titova. As the report says, on that day at about 7:00 p.m., during a thunderstorm, the ball lightning about 50 cm in diameter struck house No. 7 of M. P. Krutov and then exploded. A. S. Bystrikov arrived at the scene after 10 days. From his description it follows that electrical cables, electrical meter, the fuse panel and the window frames were put out of order. A television cable, a part of an electrical conduit, and a heating element of an electrical plate volatilized during the explosion. Eyewitnesses reported the appearance of a column of brown smoke after the explosion, and the formation of soot and cinders in the windows. Despite the fact that superficial repairs

(2) "Priroda", 1966, No. 9; 1967, No. 6; 1968, No. 8; 1969, Nos. 5 and 9; 1971, No. 6

have been done, traces of explosion were clearly visible. First of all, there was a semicircular stain on the jamb of the door; it was dark brown, with some green and yellow color on the periphery. This stain had a diameter of about half a meter, and it resembled deposits on surrounding objects after shortings. Fragments of window glass, also dark brown with a green and yellow deposit, were found dispersed at a distance of up to 10 m. In addition, a wooden decorative star covered with red material and placed on the roof of the club at a distance of 250 m from the house, suffered damage, and window panes were broken in the building. The fabric covering of the star was torn and hung like a rag, but the electrical lead to the star remained undamaged. /61

However, it was not possible to gather direct evidence that it was, in fact, ball lightning. According to the view of A. S. Bystrikov, it could also have been conventional linear lightning, striking the television antenna on the roof of the house. The X-ray analysis of deposits on glass indicated an increased content of copper and also of copper oxide (Figure 1). Apparently the television cable which volatilized during the explosion served as a source of copper.

L. V. Titova supplemented the material published by her with new data. According to this new information, the ball lightning was first observed before the open window of a store located not far from house No. 7, over the working air-conditioning units (a deafening rattle was heard at that time), and only then it proceeded towards the house of M. P. Krutov. The store servicewoman, V. Serova, observed a rather dull color of lightning with a dark-grey tint. Hence, L. Shishalova observed the sparkling lightning, which had already left the window of house No. 7. It is assumed that the lightning was moving down

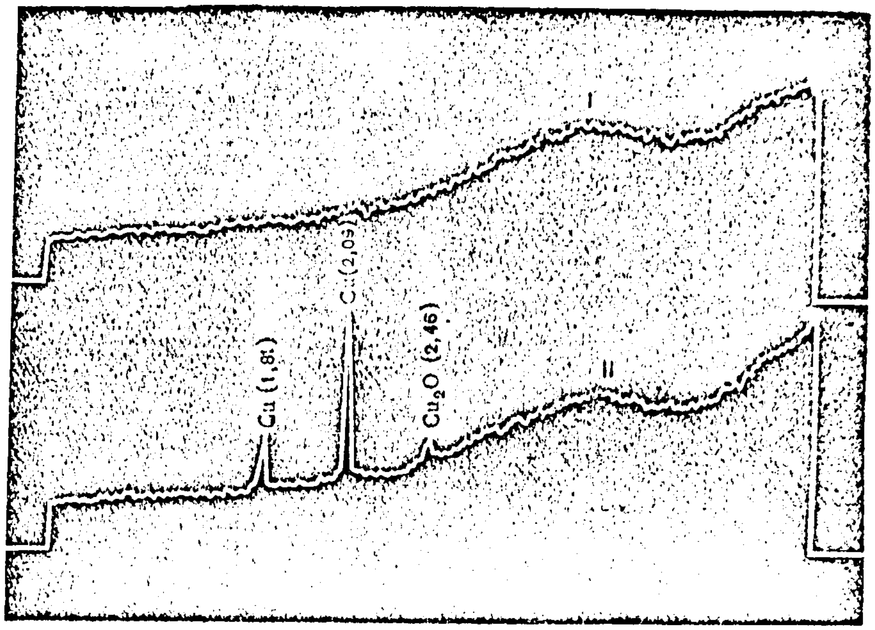

Figure 1. X-ray spectra of the window glass, obtained on a URS-50 IM diffractometer: I - a sample of the pure window glass; II - a sample of glass retaining the deposit after the possible explosion of ball lightning. The peaks on the spectrogram correspond to the crystalline materials shown, and the height of the peaks is proportional to the content of material. The numbers in brackets, given in angstroms, show the interatomic distances in the crystal lattice of the material (The data of A. S. Bystrikov).

the television cable. As pointed out by L. V. Titova, several eyewitnesses in the village observed the ball lightning, whereas nobody saw the linear lightning strike house No. 7.

We have given the description of ball lightning as reported by several eyewitnesses. But such preliminary evidence has to be followed by an analysis of observational results, mathematical modeling, and careful calculations, particularly with the application of computers. In this way, the published observational descriptions should be considered primarily as initial material for subsequent elaboration of the case in depth.[3] We shall give examples of such preliminary data.

On the basis of specifically described ball lightning observed on August 23, 1965 on the river Onega, it was established by means of calculations that the potential of lightning relative to the earth was 300-400 kV, the temperature reached the order of 14,000 degrees, the degree of ionization was 22%, the total energy reserve was estimated at 530 J, and the possible strength on explosion - 0.7 million horsepower.[4]

Photographs of ball lightnings are of particular value. Figure 2 shows one such photograph, taken by G. V. Selezhinskiy on May 30, 1972 after 10:00 p.m. during a thunderstorm over Lake Sevan (near the village of Sevan). Photographic work was being done at that time on flat, horizontal lightning, which appears on the photographs as luminescent areas. Altogether, 12 photographs were taken. After developing the films, the majority of the photographs showed parallel tracks in the form of dotted lines on the background of general luminescence. If these tracks were left by ball lightning, then we have evidence of conditions favorable for their appearance (for instance, the corresponding composition of the air) during the thunderstorm. Moreover, the dotted nature of the tracks indicates the pulsating character of the emission of lightning.

(3) The editorial board of this journal expresses thanks to all the authors who sent material concerning ball lightning. The described observations and the hypotheses advanced will be thoroughly evaluated in the appropriate laboratories of research institutes. In cases where new information becomes available, it will be published on the pages of "Priroda".

(4) ZhTF, Vol. 39, No. 2, 1969, p. 387

Interesting information was obtained from study of photographs of another ball lightning. The photograph of its track, obtained by V. M. Deryugin, was published in the previous review.[5] The negative of that photograph was subjected to microphotometric investigation. The measurements were made in our laboratory by G. A. Kalinkevich. Figure 3 shows the discovered changes in the intensity of luminescence of the ball lightning along its advance. It is apparent that the intensity of luminescence changes very irregularly; the luminescence pulsates and sometimes even fully disappears.

The same picture enabled us to establish the dependence of the luminescence intensity of various parts of a ball lightning on their distance relative to its center (Figure 4). One could expect three forms of such a dependence. If the ball lightning represents a practically opaque solid or liquid body, only the surface of the lightning could possibly serve as a source of radiation. The same conclusion would also apply to the case in which the radiation of a ball lightning is governed only by chemiluminescence, arising from a chemical reaction of its matter, for instance, a reaction of ozone and nitrogen oxides with organic compounds.[6] This possibility could follow from the experiments of G. Barri, considered earlier.[7] If, however, the radiation of the ball lightning is governed by a gaseous or plasma state (and, in limiting cases, by aerosol or other finely dispersed particles), the source of such a radiation should be matter in the lightning. Finally, the radiation could be also of /62

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(5) "Priroda", 1971, No. 6, p. 50.
(6) ZhFKh, Vol. 42, 1968, No. 12, p. 3125; ZhtF, Vol. 42, 1972, No. 10, p. 2187.
(7) "Priroda", 1969, No. 12, pp. 62-64.

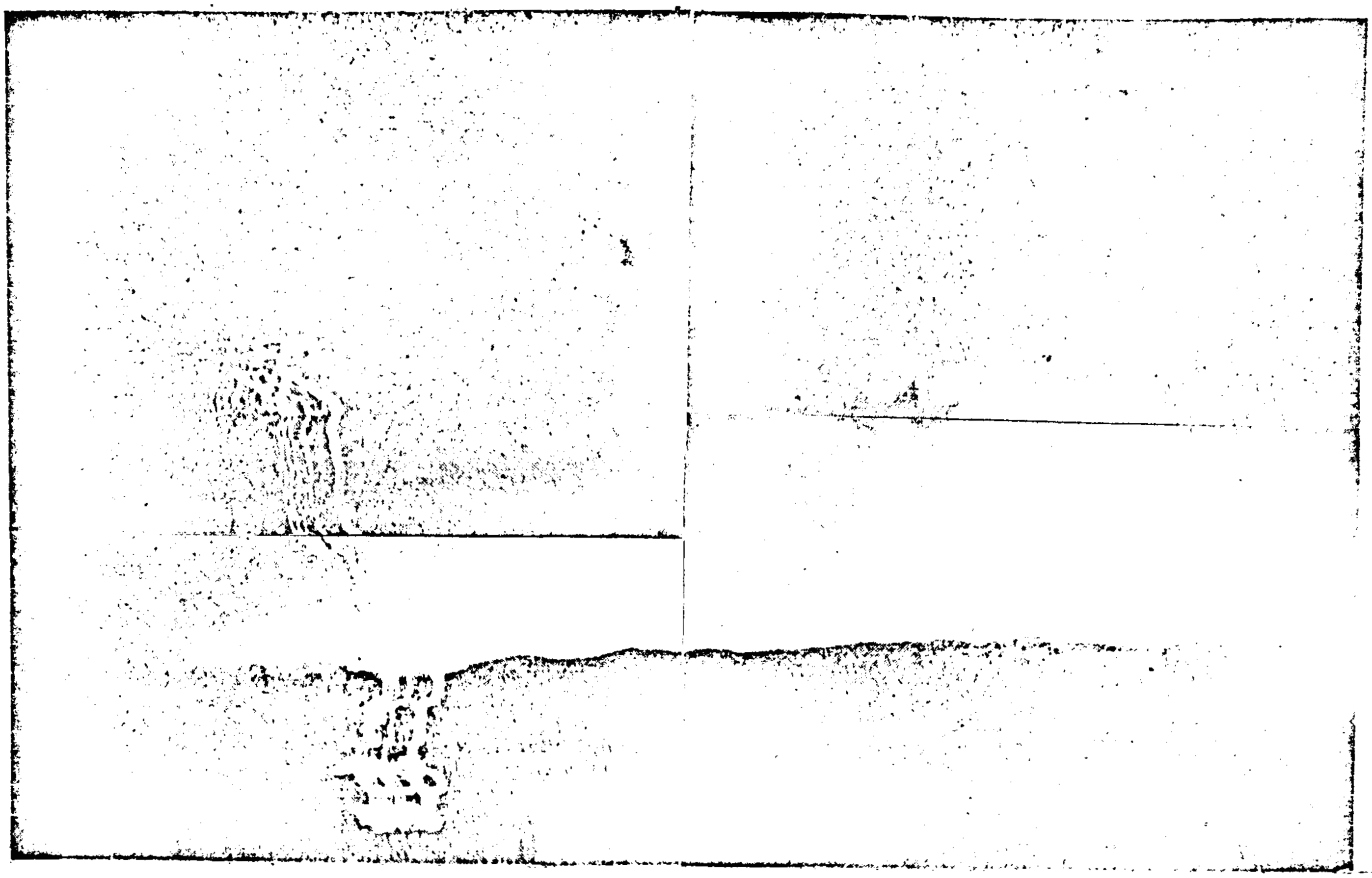

Figure 2. Photograph of the tracks of a ball lightning (broken lines) on the background of a flash of horizontal lightning, during a thunderstorm on the night of May 30, 1972 over Lake Sevan. The photograph was taken with a camera "Kiev-116" with objective "Jupiter-12" set at infinity, at nearly a fully opened diaphragm. After each flash of the lightning, the film advanced to the next frame. The film A-2 was treated with "Final" and with phenidohydroquinone developer. Because of optical effects, the track consists of 8 parallel lines. (Photograph by G. V. Selezhinskiy).

a combined nature, originating both from the volume and the surface of the lightning. The experimental data presented in the picture leave no doubt whatsoever that the source of radiation of ball lightning is within the lightning, and that the lightning itself represents matter which is primarily in the gaseous (plasma) state. Of course, these conclusions were arrived at only from separate observations of one ball lightning. Hence, for the final solution of this problem, it is necessary to accumulate further material, followed by the necessary evaluation.

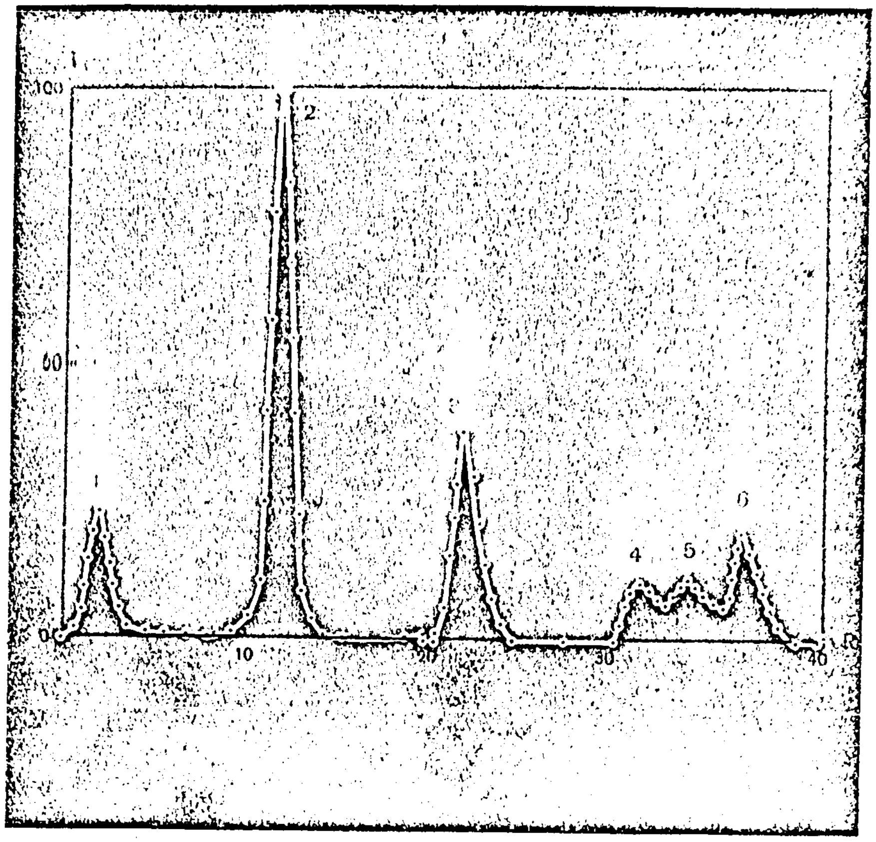

Figure 3. Changes in the luminescence intensity of the central part of ball lightning during its movement. The abscissa axis gives the distance R, measured in units of the lightning radius, and the ordinate axis shows the intensity of luminescence (its maximum value is taken arbitrarily as 100). The consecutive numbers denote the registered peaks of increased intensity. The maximum intensity corresponds to the second peak, after which and directly before the third one the luminescence at times disappears completely. After the third peak, the brightness also disappeared, but this time only at a distance 6.6 times larger than in the previous portion. It follows from these data that the luminescence of ball lightning may not be the same in different periods and that it is capable of pulsating and even becoming extinguished at times.

Recommendations to the observers

When giving examples of observations of ball lightnings and elaboration of data, we would like to remark that the authors of a number of letters, unfortunately, did not describe their observations thoroughly enough and, not infrequently, considered only the second-rate details. Therefore, we consider it desirable to offer some recommendations on how to carry out observations, and how to organize and formulate the results.

It is always necessary to pay special attention to material traces left by the ball lightning: fragments of glass, possibly /63 with molten openings, partly burned parts of cables, window frames and other objects. Their detailed investigation by means of modern methods (such as mass spectrometry, gas chromotography, radiation spectroscopy, and activation analysis) can provide new evidence about the matter or properties of ball lightning. At the site of observations, it is necessary to establish the trajectory of the lightning and to estimate the distance to it. This will enable one to determine the dimensions of the lightning, its form, rate of movement, and other properties. It is desirable to establish and make notes, if possible, of such features as the duration of the ball lightning, the color of the radiation (and its steady or variable character), the appearance of the smoke left, the nature of the odor, the damage done, etc. Apart from the behavior of ball lightning, it is also necessary to describe the circumstances under which the observations were made, and also numerous impressions.

Energy sources of the ball lightning

Undoubtedly ball lighting possesses a considerable excess of energy. It is very important to clarify what are the energy sources of ball lightning, since they assure the very existence of this lighting. In principle, three types of sources are possible: it is assumed most often that ball lightning merely accumulates energy of an ordinary thunderstorm discharge.[8] A

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[8] This type of source was considered among a number of hypotheses in the previous survey. See "Priroda", No. 6, 1971, pp. 50-59.

number of hypotheses start on the assumption that the lightning receives the energy from outside, for instance through irradiation of the clouds. Finally, we may assume the existence of a specific internal source of energy, say, in the form of a chemical or nuclear fuel. From the purely practical viewpoint, the third type of the energy source is of greatest interest. But let us at once make a reservation: this third type is the most problematic and is the least probable.

Out of many hypotheses of a specific source of energy of ball lightning, only three merit attention: the hypothesis of self-sustaining chemical reaction of the direct oxidation of nitrogen; the nuclear reaction of atmospheric xenon; and the annihilation of matter with antimatter. Let us consider each of these hypotheses separately.

The phenomenon of ball lightning is associated by V. L. Martynov with a direct self-sustaining reaction of the oxidation of nitrogen.

Frequently physical chemists were faced with the problem: could we not have an ordinary chemical reaction between the largest components of the atmosphere - between nitrogen and oxygen or water? Of course, it is easiest of all to postulate the simplest reactions of the oxidation of nitrogen:

$$N_2 + O_2 \rightarrow 2NO, \quad (1)$$

$$N_2 + 2H_2O \rightarrow NH_4NO_2. \quad (2)$$

Both these reactions are endothermic; the heat of reaction of the first is -42.3 Kcal/mole, and of the second — about

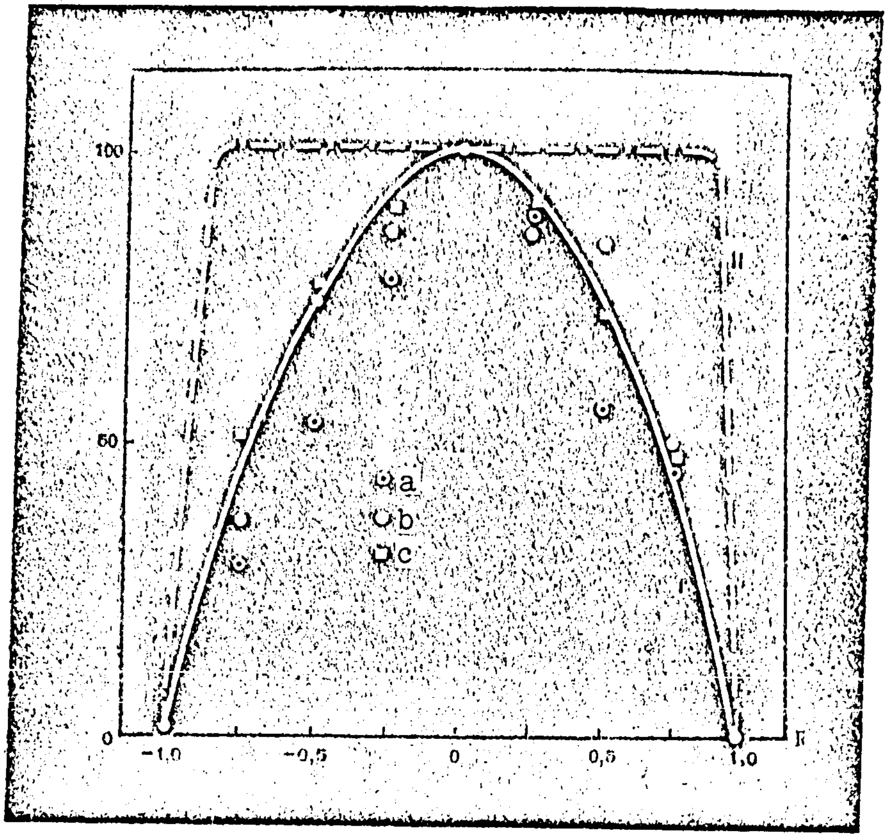

Figure 4. Luminescence intensity of various part of ball lightning. The abscissa axis gives the distance R from the center of the lightning, in fractions of its radius. The ordinates axis gives the intensity I of luminescence (its maximum value in the center of lightning was taken arbitrarily as 100). Measurements were performed for parts of the lightning trace, where the intensity of luminescence was relatively constant: a - between the 1st and 2nd peak in Figure 3; b - between the 2nd and 3rd; c - between the 4th and 5th peak. Curve I - the luminescence intensity calculated on the assumption that the matter inside the lightning serves as the source of radiation; Curve II - intensity calculated for the case where the radiation source lies on the surface of the lightning. All the experimental points lie near Curve I, leading to the conclusion that the radiation source of the lightning lies inside it.

-100 Kcal/mole.(9) Hence, under normal conditions, the possibility of the occurrence of these reactions is out of the question. /64 It is curious, however, that, after all, an experimental attempt was made to discover the reaction at increased pressures. The experiments proved to be unsuccessful. Furthermore, calculations were carried out from which it followed that, in order to form a solution of ammonium nitrite even at a concentration of 10^{-6} M, it is necessary to have the nitrogen pressure equal to 10^{51} atm. Such a pressure is, indeed, far outside the limits of practical possibilities. If, however, mixtures of nitrogen with oxygen or water are subjected to a strong physico-chemical action — for instance, heating in flames, irradiation with ionizing and ultra-violet rays, passing through electrical discharges — then we can have endothermic, i.e. energy absorbing, reactions leading to the formation of compounds with bound nitrogen. Reaction (1) was not only well studied, but was broadly utilized in Germany, Poland, Norway and Switzerland already at the end of the last century. It was utilized to obtain nitrogen oxide from the air by means of arc discharges, and to obtain nitric acid by subsequent reaction with oxygen and water.

It was already assumed at the beginning of the 20th century that one of the combinations of nitrogen, oxygen, and water has both positive heat of reaction and a negative value of the change of thermodynamic potential:

$$2N_2 + 5O_2 + 2H_2O \rightarrow 4HNO_3. \qquad (3)$$

The prominent thermodynamicist G. Lewis wrote about the possibility of this reaction as follows: "A large negative value of the free energy (i.e., thermodynamic potential ΔF) of the

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(9) The calculations made here, and further in this paper, utilized the data from the book: A. Gaydon. Dissociation energies and spectra of diatomic molecules. Moscow, IL, 1949.

formation of nitric acid shows that this compound should be obtained directly from its elements. Even starting with water and air, it is apparent that nitric acid should be obtained up to a concentration of 0.1 M, when the calculated equilibrium is reached. Let us hope that nature will not provide a catalyst for this reaction which would convert all the oxygen with part of nitrogen in the air along with water in the oceans into diluted nitric acid."[10] Thus, G. Lewis definitely considered that Reaction (3) is thermodynamically feasible, although in the same book he still adds that "nitrogen compounds need not be formed even if thermodynamically possible".

The best proof for the possible occurrence of exothermic Reaction (3) would be its experimental reproduction. Indeed, if this reaction were thermodynamically permissible, it would be sufficient for its realization to have only an initial loss of activation energy. Such conditions arise, of course, in the atmosphere (in humid air, and also over lakes and seas). Ordinary linear lightning could serve as a source of activation energy. It is difficult to say whether anybody studied exother-
mic Reaction (3) to obtain bound nitrogen. The heat of forma- /65
tion and change of thermodynamic potential of such complex reactions are calculated by combining thermodynamic data with the dissociation energies of the simplest diatomic molecules. For the dissociation energy of the molecule of nitrogen, A. Gaydon gives the value 225.1 Kcal/mole, Kh. Garstrum - 170.2, and L. Gere — only 120 Kcal/mole. Although the first of these values, based on spectroscopic data, is apparently more correct, the problem of an accurate determination of dissociation energy of a

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[10] G. N. Lewis. J. Amer. Chem. Soc., Vol. 37, 1915, p. 2308.- Cited in the book: G. Lewis, M. Randall. Chemical Thermodynamics. Leningrad, ONTIKhIMTEORET, 1936, p. 469.

molecule of nitrogen should not be considered yet as finally settled.[11] Hence, the use of different data for Reaction (3) leads to different calculation results — both for the heat of reaction and for the change of thermodynamic potential during this reaction.

According to calculations of Ya. S. Kazarnovskiy, the value of ΔF = 27.2 Kcal/mole. In other words, a positive value of ΔF, according to these data, precludes the possibility of Reaction (3) under normal conditions. Calculations of Yu. Yu. Lurye provide a negative value of ΔF, but this value is too small for reaching any definitive conclusions. If we carry out endothermic Reaction (1) in the presence of water vapor (with the possible interaction of all three reagents), then the yield of the bound nitrogen not only does not increase, but even decreases (in electrical discharges and in plasma).

It is difficult to imagine from the viewpoint of chemical kinetics the occurrence of Reaction (3) in one stage. The majority of known reactions are either bimolecular or monomolecular, and in rare cases — trimolecular. It is clear from the equation of Reaction (3) that it is necessary to have the simultaneous collision of 9 molecules for the reaction to proceed in one stage. It is quite apparent that the number of such multiple collisions is insignificant in a period of several minutes (maximum lifetime of ball lightning), and is negligibly small in comparison with the number of double or triple collisions in the same time.

Let us assume that Reaction (3) proceeds in several stages. Thus, according to Yu. Yu. Lurye, the first stage is the same as endothermic Reaction (1). After it, indeed, the studied exothermic reactions are possible:

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(11) M. V. Vol'kenshteyn. Introductory paper in the mentioned book of A. Gaydon, p. 13.

$$2NO + O_2 \rightarrow 2NO_2 + 25 \text{ Kcal/mole} \tag{4}$$

$$4NO_2 + 2H_2O + O_2 \rightarrow 4HNO_3 + + 49 \text{ Kcal/mole} \tag{5}$$

The first of them can proceed both in the gaseous and in liquid phase, and the second reaction - only in the liquid phase. This is fully understandable: 7 molecules participate in Reaction (5) and their simultaneous collision in the gaseous phase is not probable. There are no doubts whatsoever about the practical possibilities of both these reactions: they are both broadly utilized in chemical technology to obtain nitric acid and in the purification of effluent gases of nitrogen oxides. In the final result, a three-stage reaction is taking place, and its total heat of reaction amounts to 14.5 Kcal/mole.

The most thorough calculation of the thermodynamic potential change in Reaction (3) gave the value $\Delta F = -4$ Kcal/mole, i.e., this reaction appears to be thermodynamically possible. Nonetheless, it has to be remembered that an input of a large energy is required to carry out the first stage of this reaction, and, on the basis of current data, it is difficult to visualize any kind of intermediate active particles or catalysts which might accelerate Reaction (3). It is known that molecular nitrogen practically is not oxidized by means of atomic oxygen or ozone. Also, the catalysis of the direct oxidation of nitrogen at sufficiently high temperatures proved to be ineffective. Moreover, Reaction (5), in its turn, is complex and takes place effectively only in the liquid phase. Finally, the possibility is not excluded that the negative value of the change in thermodynamic potential and positive value of the heat of reaction are a consequence of some error in determining the dissociation energy of some of the simplest molecules.

It should be noted that various investigations of the reaction of the direct oxidation of nitrogen, including experiments in a plasma and in a nuclear reactor, gave an energy yield not exceeding 10 atoms of bound nitrogen per 100 eV.[12] In other words, the degree of utilization of energy for the chemical reaction did not exceed 9.2% in this case; but, to have a reaction which is self-sustaining to any degree, the degree of utilization of initial energy should exceed considerably 100%. Nevertheless, the possibility of such a process is still of some interest. If the air, in conjunction with the hypothesis of the self-sustaining reaction of the oxidation of nitrogen, represents merely a chemical fuel, then 1 m^3 of air could provide 27 watt-hours of energy. In addition, experimental implementation of such a self-sustaining oxidation reaction would provide for mankind a large source not only of energy but also of bound nitrogen (up to 90 g per 1 m^3 of air). However, this hope is lost if it is found that the ball lightning merely accumulates the energy of linear lightning (the first type of source).

Studies were made of the stability mechanism of ball lightning, based on the reaction of active nitrogen in a low-temperature plasma.[13] The following well-known process was utilized:

$$N_2^+ + O_2 \rightarrow NO^+ + NO. \quad (6)$$

This reaction is strongly exothermic. At ionization of 20%, the evolved energy reaches 0.883 kilowatt-hour per 1 m^3 air. Thus, it is seen that no additional energy can be obtained from

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(12) M. T. Dmitriyev. Prakticheskiye aspekty radiatsionnoy khimii vozdukha. "Izotopy v SSSR" (Practical Aspects of the Radiation Chemistry of Air. "Isotopes in the USSR"), Atomizdat, 1970, No. 17; Atomnaya energiya, Vol. 15, No. 1, 1963, p. 52.

(13) M. T. Dmitriyev. ZhTF, Vol. 39, No. 2, 1969, p. 387; Vol. 42, No. 10, 1972, p. 2187; Wissenschaftliche Zeitschrift der Technischen Hochschule Ilmenau, Vol. 16, No. 5, 1970, p. 87.

the air, since we have to expend 3.5 times more energy to form the required initial concentration of nitrogen ions (but in natural conditions this is possible during the discharge of a linear lightning). /66

According to another hypothesis, nuclear reaction of atmospheric xenon serves as an actual source of energy for ball lightning. The author of this hypothesis, V. I. Arabadzhi, considered a number of properties of ball lightnings and pointed out that in the majority of cases they present spherical forms, but also not infrequently they are pear-shaped or even have an irregular form. They originate both at the ground level (in which case the diameter of the lightning reaches 10-20 cm), and also at the level of clouds (but then with a diameter of up to 10 m). The existence of ball lightning varies between a fraction of a second up to 4 minutes. In the majority of cases, the disappearance of the lightning is associated with an explosion, equivalent in strength to the explosion of 0.1-1 kg TNT (sometimes even up to 10 kg TNT). Separate considerations are given to mobile lightning (independently floating in the air), and to immobile lightning (attached to sharp objects, coaxial to lightning arrestors).

In the view of V. I. Arabadzhi, the energy source of ball lightning may be the inert gas xenon in the atmosphere. One of the isotopes of xenon is a unique element in the composition of the atmosphere. The concentration of xenon in the atmosphere under normal conditions is $8.6 \cdot 10^{-6}$%, or 0.51 mg/m^3. According to this hypothesis, the formation of ball lightning in the air is possible, because sometimes there is a focusing of nucleo-active cosmic particles in a strong electrical field of thunderstorm clouds. In those cases where additionally a cosmic particle of high energy passes along the axis of a focused beam, it is possible to have a multiple generation of new particles with the formation of mesons. From the equilibrium between the energy evolved in the lightning at the non-chain fission of xenon nuclei, and the energy dissipated by the lightning in the form of optical radiation, one can estimate the concentration of fissionable xenon nuclei necessary for the existence of the lightning. At the average energy of 8 Mev, evolved by each fissionable nucleus in 1 sec, lightning temperature of 2500°K and a diameter of 40 cm, the necessary concentration of nuclei is $2.6 \cdot 10^{12} cm^{-3}$. In order of magnitude, this value coincides with the natural concentration of xenon in the air, $2.7 \cdot 10^{12} cm^{-3}$.

V. I. Arabadzhi considers also that we can assume that ball lightning is supported not only by the instantaneous ($\sim 10^{-14}$ sec) emission of the fission neutrons, but also by delayed neutrons emitted by fissionable nuclei during a time from several seconds to several minutes with constantly decreasing intensity. When the energy is dissipated gradually, the lightning can be extinguished quietly. In cases of fast evolution of energy and the sharp drop following it, an explosion of lightning is possible. Since the escape of nucleo-active particles and the radiational losses should be minimal from a spherical volume, the most long-lived should be lightning of a ball shape. According to this hypothesis, the probability of ball lightning formation should correlate with strong solar flares, accompanied by a considerable increase in corpuscular cosmic radiation on the Earth's surface.

What can we say about the arguments for this hypothesis? Indeed, B. Schonland in his geophysical investigations in South Africa established that the intensity of the charged component of cosmic radiation is increased in some places (and decreased in others) under a thunderstorm cloud, in comparison with a cloudless space — and this could be explained also as focusing of cosmic particles in the electric field of thunderstorm clouds.[14] Moreover, the time of existence of ball lightning coincides in order of magnitude with the time of emission of delayed neutrons.

However, all this is still insufficient to confirm the hypothesis of nuclear reactions of atmospheric xenon as a source of energy for ball lightning. In particular, this hypothesis is unable to explain the formation of ball lightning at the cloud level (and even less so - above the clouds), the independent features of mobile lightning, the long immobility of axial lightning, etc. Other questions also require answers. For instance, it is necessary to estimate what should be the intensity of a beam of cosmic particles to heat a volume of air of about 30 liters (a ball of 20 cm radius) to the assumed temperature of 2500°K on account of the energy of fission of xenon nuclei. Are such intensities encountered under natural conditions? Apparently, the beams of neutrons created in nuclear reactors exceed considerably the beams of cosmic rays under real conditions, even assuming their focusing. Further, it is necessary to take account of heat losses in the lightning as a result of the necessary mass transfer, since without mass exchange the lightning would not be able to exist more than 1 sec, because of the exhaustion of xenon contained in it. Under conditions of a constant mass exchange governed by displacement of the focusing area together with the cloud, the role of delayed neutrons, emitted during a time of up to several minutes, becomes insignificant for maintaining the lightning. Finally, it would be of interest to determine experimentally the degree of possible focusing of cosmic particles in the field of thunderstorm clouds.

(14) B. F. Schonland. Atmospheric Electricity. Pergamon Press, 1953, pp. 21-58.

If such a focusing would in fact be possible, it would result inevitably in lethal irradiation of animals or men who happened to be under it, and this effect certainly would be observed in nature. However, until now such facts have not been registered, despite the fact that irradiation injuries are established at the present time with practically absolute certainty.

If separate occurrences of both the nuclear and chemical reactions are feasible, there is no apparent obstacle to their simultaneous realization leading to obtaining bound nitrogen. It is obvious that bound nitrogen can be formed by carrying out only one nuclear reaction; in this case the fixation of nitrogen will follow the already studied endothermic process (6) with a /67
yield of up to 140 g per 1 m^3 air. It is still too soon to say if even one of these reactions will ever be practically utilized as a cheap source of energy, since so far these reactions have not yet been accomplished.

Let us consider still another possible nuclear energy source of ball lightning. It is based on the reaction of annihilation of matter with antimatter.

Observations made in recent years by means of satellites and space vehicles on cosmic irradiation made it possible to make estimates of the fraction of antimatter in interstellar space. Assuming uniformity of the mixture of matter and antimatter in the closed Universe [15], the fraction of antimatter cannot exceed 10^{-7}. Since this value is not small, then considering the total amount of finely dispersed meteoritic matter

[15] G. L. Vardenga, E. O. Okonov, Priroda, No. 10, 1971, p. 56.

falling on the Earth ($3-5 \cdot 10^6$ tons per year), [16] the fraction of antimatter would be more than sufficient (up to 500 kg antimatter per year). It would be more than sufficient to explain by the influx of antimatter all the observed ball lightnings, under the condition, of course, that antimatter is able to penetrate to the surface of the Earth without annihilation.

This hypotheses was advanced in the scientific literature by D. Ashby and K. Whitehead. According to them, ball lightning is formed by annihilation of the particles of antimatter in the Earth's atmosphere.[17] It is assumed that antimatter enters at first the upper layers of atmosphere in the form of micrometeorites [18] having a diameter of several micrometers. As long as the velocity of penetration by antimatter particles of the atmosphere toward the surface remains small, the annihilation may not occur. Since the probability of annihilation of external positrons should be considerably higher than that of antinuclei, the micrometeorites should be ionized in the upper atmosphere; the charge of these particles is negative. Further, the authors of this hypothesis assume that during thunderstorms, the micrometeorites of antimatter are captured by linear lightning and, in the process of discharge, reach the surface of the Earth. At the same time, antimatter particles are accelerated to such an extent that their annihilation becomes possible. The energy evolved in this process causes the ionization and excitation of the molecules in the air, and this is manifested in the form of bright luminescence of the ball lightning.

(16) A. V. Ivanov, K. P. Florenskiy, Astronomicheskiy vestnik, No. 1, 1971, p. 12.

(17) Nature, 1971, March, p. 19; Science News, Vol. 99, No. 14, 1971, p. 226.

(18) The possibility of micrometeorites being of antimatter nature was considered by B. P. Konstantinov and coworkers. See: Kosmicheskiye issledovaniya, No. 1, 1966, pp. 66-74.

As is known, the process of annihilation generates as a by-product also λ-radiation with an energy of 511 KeV (about 30% of the total energy of annihilation). D. Ashby and K. Whitehead carried out observations on some actual ball lightning, and in four cases the presence of λ-radiation was established. In one of those cases, the energy appeared to be close to 500 KeV, although the authors do not consider this fact yet as sufficient evidence for their hypothesis.

Thus, the hypothesis in which the reaction of annihilation of antimatter micrometeorites serves as a source of energy for ball lightning is of definite scientific significance. Nevertheless, it is necessary to make some critical remarks.

First of all, no single credible case of the fall of an antimeteorite on Earth has yet been established. On the other hand, the last decades have witnessed a large expansion of radar investigations of meteoritic traces and their utilization, particularly for radio communication in polar regions. So far, there is no evidence of any kind that on the background of the general stream of meteorites there are encountered, at least to a small degree, separate anomalous meteorites possessing an exclusively high ionization capability. Let us assume, despite all this, that micrometeorites of antimatter do reach the Earth's atmosphere. In this case, it is important to establish what is their lifetime in the atmosphere, to what altitude the antimatter in the form of micrometeorites can approach the surface of the Earth, and can it thus reach the clouds?

In this hypothesis, ball lightning is formed only by those micrometeorites which fall into the channel of linear lightning and are further accelerated by it. Consequently, the creation of ball lightning may involve participation of a quite insignificant portion of the total possible amount of antimatter in the atmosphere — for example $2 \cdot 10^{-8}$, i.e., not more than 10 mg antimatter per year, which makes this hypothesis even less credible. Finally, even if a micrometeorite does fall into the channel of linear lightning, then at temperatures of about 50 thousand °K the material should vaporize, and the surface would be reached only by separate atoms. And each separate atom, in fact, will not evolve a sufficient amount of energy on annihilation. If we assume the movement of an ionized particle with a diameter of several micrometers in the channel of linear lightning, then with a mobility of such mono-charged particles no higher than $5 \cdot 10^{-5}$ $cm^2/V \cdot sec$, a field potential of about 10^3 V/cm, and a duration of discharge no more than 0.05 sec, such a particle can pass along a distance of only $3 \cdot 10^{-3}$ cm on the channel. Even if the charge on the micrometeorite increased because of annihilation of external positrons, it is still difficult to assume that this distance might exceed several centimeters.

Thus, whatever is the physical nature of ball lightning, it should possess some minimum energy excess for its existence. However, it does not follow from this that the energy source of lightning should be entirely unconventional from the viewpoint of modern physical concepts.

It will take still future investigations to show which are the sources of energy that feed the still-enigmatic ball lightning.

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16. Abstract

Detailed descriptions are given of observations of ball lightning. The possible sources of energy for ball lightning are discussed. These are self-sustaining chemical reactions of the direct oxidation of nitrogen, the nuclear reaction of atmospheric xenon, and the annihilation of matter with antimatter. No definite conclusions are reached.

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